Observational Studies of Potential Progenitors of Type Ia Supernovae

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Abstract: The identification of the progenitor class(es) of Type Ia supernovae (SNIa) has been a long-standing problem in modern astrophysics. The importance and urgency for solving this problem has increased markedly over the last decade as SNIa have become an essential tool for cosmology. A clearer understanding SNIa progenitors can help address the significant (±0.6 mag in V) scatter in the raw peak absolute magnitudes of SNIa: they are a good standard candle only after an empirical stretch correction has been applied (Phillips 1993). While it is widely accepted that this does not introduce a systematic bias to the *current cosmological inferences* based on SNIa data, future use of SNIa for precision cosmology, such as the Joint Dark Energy Mission envisions, requires that we further reduce any systematic effects. We believe that, to gain confidence in the cosmological results, we must achieve a physical understanding of the white dwarf parameters that contribute to the scatter in peak luminosities, and why the empirical correction works as well as it does. Only then will we be able to assess the magnitude of any cosmological evolution of the stretch correction factor.

In this white paper, we outline a program of observational research on potential SNIa progenitor classes within the single degenerate channel, in the context of ongoing research into various classes of accreting (and often nuclear burning) white dwarf binaries. Two key parameters that we must measure to securely identify SNIa progenitors are the current mass of the white dwarf, and the growth rate of the white dwarf mass. We must also measure other system parameters, such as the white dwarf spin and the metallicity of the system, that have the potential to affect the properties of the eventual supernova. Because the X-ray band offers the best chance to observe the white dwarfs directly in the potential progenitor binaries, we concentrate on observations using the proposed International X-ray Observatory mission.

Candidate SNIa progenitor classes

A galaxy with a representative rate of 3 SNIa explosions per millennium must contain 3,000 progenitors within a million years of explosion. If all SNIa occur at the Chandrasekhar mass, and if the mass of progenitor white dwarfs grows at a representative rate of $\sim 10^{-7}$ $M_\odot\,yr^{-1}$, then these 3,000 progenitors must harbor massive white dwarfs within 0.1 $M_\odot$ of the Chandrasekhar limit. While the Milky Way probably contains millions of accreting white dwarf binaries, the majority contain a much lower mass and will never evolve to an SNIa. To be considered a SNIa progenitor, the accretor must be a CO white dwarf, implying an initial mass of < 1.1 $M_\odot$; and yet it must be able to grow to the Chandrasekhar limit. Thus, SNIa progenitors are a special subset of accreting white dwarf binaries.

Cataclysmic variables (CVs), in which a white dwarf accretes material lost from a Roche-lobe filling, late type star, are a common type of interacting binaries, with an estimated space density of $\sim 10^{-5}$ pc^{-3} in the solar neighborhood (see, e.g., Pretorius et al. 2007 and references therein). In addition, accreting white dwarfs can be found in many symbiotic stars, in which an M giants is accompanied by a hot blue component and nebular emission lines[1]. In this case, accretion is probably via a wind, although Roche lobe overflow cannot be excluded in some cases. The population of symbiotics with accreting white dwarfs is highly uncertain: Munari & Renzini (1992) claim that existing observations were rather inefficient at discovering them, and they estimate a total Galactic population of 3×10^5, $\sim$100 higher than the typical estimates.

The M giant mass donor dominates the optical/IR emission from symbiotics. Excluding this, the dominant energy sources in CVs and symbiotics are accretion (typical efficiency: 0.03%) and nuclear fusion (0.7%). If the accreted matter becomes degenerate, then accretion results episodes of thermonuclear runaways on the white dwarf surface, known as classical nova outbursts. The higher efficiency of nuclear fusion means that it can generate sufficient energy to expel all the matter that has been accreted and more, as has also been inferred from observations (Gehrz et al. 1998). Therefore, the white dwarf mass in CVs may not grow over multiple nova cycles.

A thermonuclear runaway starts when a sufficient amount of mass is accreted to create a high enough pressure and density at the base of the accreted envelope. For a typical CV, this might take 10^4–10^5 years. Such systems are only seen to undergo nova outburst once, and are known as classical novae (CN). The mass of white dwarfs in CN systems may stay constant or even decrease over multiple nova cycles. However, there are about a dozen systems that have been seen to undergo multiple thermonuclear runaways over the last century or so: these are known as recurrent novae (RN), and can occur either in CV or symbiotic systems. To be able to reach the critical density in a few decades, RN must have a white dwarf near the Chandrasekhar limit (see, e.g., Yaron et al. 2005 for a recent quantitative result on the white dwarf mass vs. the recurrence time). Moreover, RN are thought to be able to grow in mass through successive thermonuclear runaways. RN are therefore candidate progenitors for SNIa. Although the number of known RN is small, our current census of RN is far from complete. Considering the discovery probability of nova outbursts, Schaefer (2009) estimates that thousands of Galactic RN have remained unknown or unrecognized. If true, RN can be an important SNIa progenitor channel.

When the accretion rate is high (of order 10^{-7} $M_\odot\,yr^{-1}$) and the white dwarf is hot, the hydrogen-rich layer never becomes degenerate, thus preventing a thermonuclear runaway. Instead, continuous nuclear fusion occurs in such a system, making it a quasi-steady supersoft source (SSS; Kahabka & van den Heuvel 1997). Such non-explosive burning suggest SSS white dwarfs should grow in mass, and they are therefore excellent candidate SNIa progenitors (Hachisu et al. 1999). A closely related phenomenon is the SSS phase of CN and RN, which often follows the initial explosion and may last for weeks to years; this suggests that hydrogen rich material is available on the white dwarf surface after the nova eruption, reopening the possibility of secular mass growth in CN. SSS are luminous ($\sim 10^{38}$ $ergs\,s^{-1}$) sources of X-rays below $\sim$0.5 keV. Because the interstellar medium readily absorbs such soft X-rays, only a fraction of Milky Way SSS can be detected. Our best chance to conduct a census of SSS therefore is in the Local Group galaxies with low foreground absorption. Already, the majority of the known SSS are in M31 and in the Magellanic Clouds.

The ultimate goal that we advocate in this white paper is to identify what types of accreting white dwarf binaries are significant as SNIa progenitors. In addition to the

[1]In this white paper, we ignore other types of symbiotics, such as those with a neutron star or a main sequence accretor.

ongoing effort to obtain an accurate estimate of their populations, we must measure, in a representative sample, the white dwarf mass and the mass growth rate; we must also measure parameters of the progenitor white dwarfs that can potentially affect the properties of the SNIa explosions.

Progenitor parameters of interest

The most important parameter governing the observables of SNIa explosions is the thermonuclear yield of ^{56}Ni, whose radioactive decay powers the visible emission. We discuss the metallicity and the spin of the white dwarf as two parameters with potential to affect the ^{56}Ni yield of SNIa. We have singled out these parameters because they have already been identified as potentially important. If other parameters are identified or suggested as important, we will adjust our observing plans accordingly.

In the model of Yoon & Langer (2005), in which the angular momentum is transported primarily via the Kelvin-Helmholtz instability, accreting white dwarfs spin rapidly, and can reach a mass as high as 2.0 $M_\odot$. This is far above the canonical 1.4 $M_\odot$ Chandrasekhar limit, with obvious consequences for the SNIa properties. In fact, processes neglected by Yoon & Langer are likely to exclude the possibility of such extreme super-Chandrasekhar mass white dwarfs (see, e.g., Piro 2008). Nevertheless, angular momentum transport onto, within, and out of a white dwarf is a complex problem. We therefore believe that the white dwarf spin can still play a less extreme, but nevertheless significant, role in SNIa explosions. Note that, in the absence of angular momentum loss, an accretion of $\sim$0.1 $M_\odot$ via a Keplerian disk is sufficient to spin the white dwarf to near break-up rate. In CVs, such rapid spin is generally not seen (Starrfield et al. 2003), which is interpreted as due to an efficient removal of angular momentum during nova outbursts. It remains to be seen if angular momentum can be removed equally well from SNIa progenitors, including SSS which do not experience nova outbursts.

The degree of neutron excess in the white dwarf is known to alter the yields of ^{56}Ni and other iron group elements (Timmes et al. 2003). Badenes et al. (2008) compared the measured ratio of Mn to Cr in the *Suzaku* X-ray spectrum of Tycho's supernova remnant with that predicted by SNIa models with different degrees of neutron excess. The white dwarf that exploded as Tycho's supernova had a high degree of neutron excess, from which Badenes et al. infer that the original progenitor had a super-solar abundance, since this leads to higher amount of ^{22}Ne in the white dwarf, the primary source of neutron excess in a CO white dwarf. Once we securely identify the SNIa progenitor populations, we can study their age and metallicity distributions and calculate what this would imply for the ^{56}Ni yields of a population of SNIa. This can be done observationally for local group galaxies, and theoretically for galaxies at cosmological distances.

Outline of a possible observational program

Studies of CVs and symbiotics in general have a long history, and have benefited from the recent advances in astronomical observations (X-ray and UV observations from space, and the Sloan Digital Sky Survey, for example). We assume that these studies will continue, using existing and near-future projects that are outside the scope of this Decadal Survey.

We must single out one future project that could have a large impact on the field: The

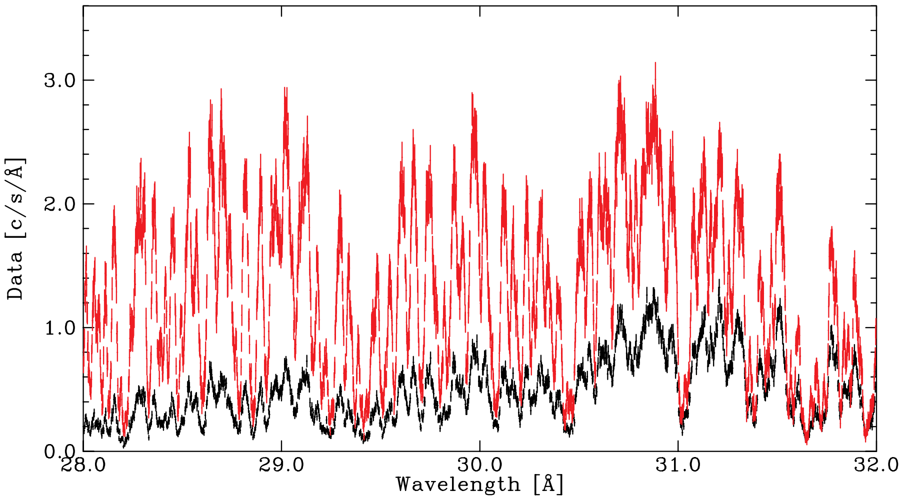

Figure 1: A section of the simulated IXO/CAT spectra (Leutenegger 2009) of the SSS, CAL 83, for an integration time of 100 ksec and using a version of the response that assumes A=3,000 cm^2 and R=3,000. Both the first order (black) and the second order (red) are shown, based on the spectral model of Lanz et al. (2005).

German eROSITA instrument on the Russian Spectrum-X-Gamma mission scheduled for launch in 2011. It will perform a sensitive all-sky survey of the 2–10 keV band, in which CVs and symbiotics are an important source class. Prominent 2–10 keV emission is produced by optically thin plasma shock-heated to high temperatures (kT $\sim$ 10–50 keV) when the accreting flow hits the white dwarf surface. The plasma temperature depends on the accretion geometry (i.e., whether the white dwarf is magnetic or not) and on the white dwarf mass. Many CVs and symbiotics are hard X-ray source with luminosities in the $10^{29} - 10^{34}$ $\mathrm{ergs\,s^{-1}}$ range. The number of eROSITA CVs and symbiotics could easily be in the thousands,

CVs and symbiotics that are more luminous and harder contain either a magnetic white dwarf or a high mass one. SNIa progenitors (those with near Chandrasekhar-mass white dwarfs) have the deepest gravitational potential, and should be prominent in the eROSITA sample. We have already discovered a few potential SNIa progenitors that are luminous X-ray source. Most notably, the recurrent nova T CrB is now known to be a $\sim 10^{34}$ $\mathrm{erg\,s^{-1}}$ source through detection with Swift BAT above 14 keV (Kennea et al. 2009), and the eROSITA survey will be orders of magnitude more sensitive.

Because of these hard X-ray emissions, and the supersoft (<0.5 keV) emission from nuclear burning white dwarfs, the International X-ray Observatory (IXO) will have the most impact on this field, among the missions to be evaluated by this Decadal Survey. Note that, in high accretion rate CVs and symbiotics, the accretion disk outshines the white dwarf in the optical and the UV. The X-ray band therefore is the key that allows us to study the white dwarf parameters in these systems.

In the following, we assume IXO with both the calorimeter instrument and a grating spectrometer (specifically, we assume Critical Angle Transmission grating spectrometer, CAT, with a resolution (R) of 3,000 and an effective area (A) of 3,000 cm^2).

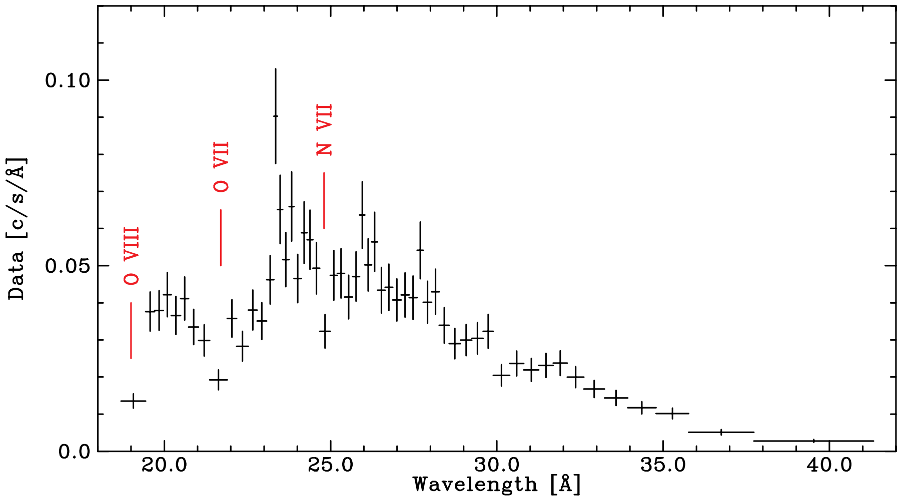

Figure 2: A simulated IXO grating spectrum of the M31 SSS, r2-12. For this simulation, we have used the baseline design of A=1,000 cm^2/R=3,000, and assumed a 5 ksec exposure. This demonstrates the ability of IXO grating spectrometer to detect spectral features in SSS in M31, allowing the first reliable determination of spectral parameters.

[1] Detailed spectroscopy of nearby SSS

The IXO grating will allow us to study nearby SSS in unprecedented details, including CAL 83 and CAL 87, the well known SSS in the Large Magellanic Cloud (LMC), and of SSS phase of Galactic novae that are close enough for extinction not to matter. We show an example in Figure 1, which is a simulation of a 50 ksec IXO/CAT observation of CAL 83. Such high signal-to-noise, high resolution spectra of the supersoft emission, combined with the continuing improvement in the stellar atmosphere models, will allow us to measure the effective temperature and abundances of the atmosphere, and infer the mass and the size of the white dwarf, with a high degree of accuracy and confidence. Moreover, we will be able to constrain any rotational broadening of the spectral features.

In contrast to CAL 83, the X-ray spectrum of CAL 87 is dominated by redshifted emission lines, suggestive of an wind origin (Orio et al. 2004). Such wind lines indicate mass loss from the SSS. We will search for wind features in a sample of SSS and evaluate the efficiency of mass growth of white dwarfs in quasi-steady SSS.

Observations of SSS of novae with Chandra and XMM-Newton gratings have revealed a puzzle: they are highly variable, with both (quasi-?)periodic and periodic variability. Time scales can be as short as $\sim$35 s in RS Oph to 1.7 days in V458 Vul. IXO will allow us to address this problem, because we can obtain high S/N spectra of bright novae in outburst with only a 500 s exposure with the CAT, sufficient to determine the temperature accurate to 5%, and the absolute flux to 10–15%. This means we can learn what, physically, is changing on these timescales, by studying "clean" spectra, not superpositions of different spectra at different times. To understand the secular mass change in CN and RN, we need to estimate the amount of hydrogen rich material that is left after the nova outburst, and how and when the SSS phase terminates. Solving the puzzle of the rapid variability may be a necessary step in such a complete understanding of the SSS phase of CN and RN.

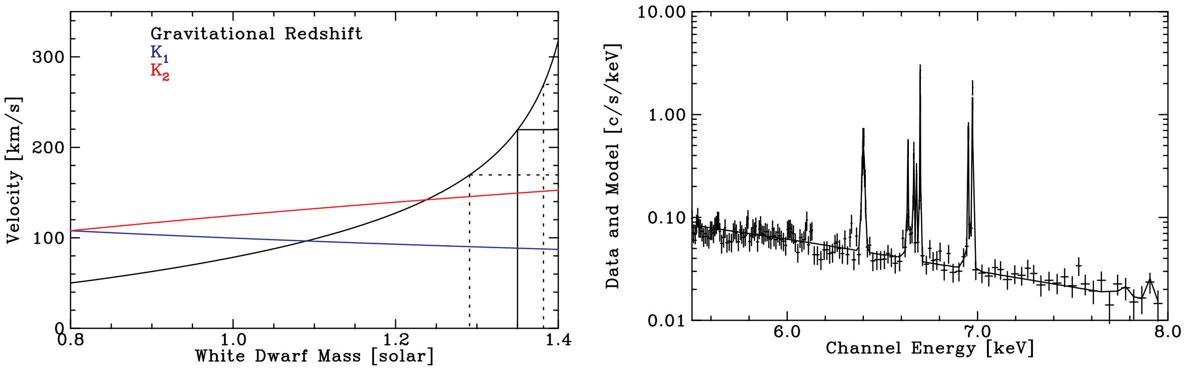

Figure 3: (Left) The gravitational redshift expected for white dwarfs in the 0.8–1.4 $M_\odot$ range (black). Also shown are the radial velocity semi-amplitudes of the white dwarf (blue) and mass donor (red) for an assumed 1-d binary with an 0.8 $M_\odot$ mass donor and an inclination of 60°. A measured gravitational redshift of 220±50 $\mathrm{km\,s^{-1}}$ will constrain the white dwarf mass to be $1.35^{+0.031}_{-0.059}$ $M_\odot$. (Right) A simulated IXO calorimeter spectrum of a $\sim 10^{32}$ $\mathrm{ergs\,s^{-1}}$ (2–10 keV) accreting white dwarf at an assumed distance of 1 kpc, for a 50 ksec observation. The simulation includes a reflection line at 6.4 keV line (130 eV equivalent width) in addition to the multi-temperature thermal emission. The line centroid can be determined accurately to about ±1 eV, or ±50 $\mathrm{km\,s^{-1}}$, in this simulation.

[2] Spectroscopy of a sample of SSS in the local group

To date, 90 SSS have been observed in M31 at different times, and in about 80 cases we can exclude a supernova remnant or AGN interpretation at high confidence. Of these, 19 are almost certainly CN in the few years after the outburst, due to coincidence in space and time. About 50% of M31 SSS were either detected only once, or are in regions of M31 where only an old population exists, according to the color-magnitude diagrams of the error circles. We conclude therefore that the fraction of CN and RN among SSS in M31 could be as high as 50%. Of the remaining objects, we know that at least 40% (∼20% of the whole population) are associated with a young population and often found in star forming regions. These SSS seem to be mostly transient, or recurrent transient, and most of these are bright. One such case is source r2-12 detected at 0.277±0.003 $\mathrm{c\,s^{-1}}$ with XMM-Newton. We show a simulated IXO/CAT spectrum of this source in Figure 2. We find that, in 5 ksec, we will be able to determine the effective temperature accurate to 7%.

The IXO wide-field imager will allow us to select SSS that are in a bright state for CAT observations anywhere in the Local Group, except in the most crowded regions. Unlike CCD resolution X-ray data (available from Chandra and XMM-Newton observations), the CAT data will reveal spectral features that and allow temperature and other key parameters of SSS to be measured. Our short exposure time simulation demonstrates the potential to do so on a large number of local group SSS, which is potentially a large enough sample that we can better assess their importance as SNIa progenitors.

[3] Hard X-ray bright non-magnetic white dwarfs

Although the majority of the accreting white dwarfs detected above 10 keV with INTEGRAL and Swift BAT are magnetic CVs, there is no evidence for a magnetic white dwarf to date in the 4 symbiotics detected by BAT (Kennea et al. 2009), including the known recurrent nova T CrB. Kennea et al. argue that these 4 symbiotics are indeed non-magnetic, and that the high temperature and luminosity of these objects are due to the deep gravitational potential of massive white dwarfs. Similarly, of the two novae detected as X-ray sources before their respective outbursts, V2487 Cyg (Hernanz & Sala 2002) is now known to be an RN (Pagnotta et al. 2008) and V2491 Cyg (Ibarra et al.2008) may also be recurrent: it may be that their high X-ray luminosity is also due to the high mass.

The 6.4 keV fluorescent line is commonly seen in accreting white dwarf binaries. This line is produced at the white dwarf surface when it is irradiated by >7 keV photons, and is therefore subject to a gravitational redshift. The expected magnitude of this (Figure 3, left) is such that it can be detected by an IXO observation (Figure 3, right), provided that the systemic velocity is known from ground based spectroscopy, for high mass white dwarfs. In fact, the steep increase in the gravitational redshift makes it the method of choice for identifying near Chandrasekhar-mass white dwarfs. We propose a program of IXO observation of known hard X-ray bright RN and CN, as well as other hard X-ray bright accreting white dwarfs whose number will have increased dramatically through the eROSITA survey. Together with the continuing effort to uncover more RN through the detection of multiple outbursts, such a program will assess how significant RN are as a class of SNIa progenitors.

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